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Optimal integration time in OCT imaging

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ABSTRACT

When measuring static objects with 3D OCT, two opposing trends occur: If the integration time is too short, the measurement is noisy resulting in granulated textures on measured objects. If the integration time is too long, drifts e.g. due to thermal effects or unstable laser sources lead to blurred images. The Allan variance is a scheme to find the optimal integration time in terms of reducing noise without picking up signal drift. A long-term measurement with short integration time of a reference target under realistic conditions is needed to obtain the database for the calculation of the Allan variance. Longer integration times are simulated by taking averages of subsequent samples. The Allan variance being the mean of the squared differences between two consecutive averages is calculated for different integration times. The optimal integration time is achieved for minimal Allan variance. First, the scheme is explained and discussed with simulated data. Then, reference measurements of layers of adhesive tape made with a 3D OCT device are analysed to find the optimal integration time of the device. Finally, the findings are applied to the detection of water inclusions in calcite. With too short integration time the water inclusions appear with a stained surface. With the integration time increased towards the optimal time, the surfaces of the water inclusions get smoother and easier to discriminate from the background. Ready-to-use Octave code for the computation of the Allan variance is provided.

Keywords: Allan variance, optimal integration time, noise vs. instrument drift

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1. INTRODUCTION

Optical Coherence Tomography (OCT) has proven to be a valuable tool for 3D imaging of partly transparent and scattering objects. In recent years, the size reduction of OCT systems together with growing computer power have lead to mechanically and computationally fast OCT devices enabling the examination of objects in motion, such as the human eye.[1] However, fast caption of OCT images requires short integration times in the signal acquisition resulting in image noise.

On the other hand side, if the sample examined with OCT is not moving and temporally stable in its structure, the integration time can be increased for the benefit of a better signal-to-noise ratio. But in reality, a signal is never completely constant and drifts, typically due to thermal dilatation or mechanical vibrations in the OCT device, gain fluctuations of amplifiers or unstable laser sources. As a consequence, the integration time must be limited so that the measurement remains unaffected by long-term changes of the signal. Moreover, too long integration times unnecessarily increase the image acquisition time.

Hence, there exists an optimal integration time for an OCT signal to such a degree as the noise is reduced without picking up drift effects. David W. Allan proposed the calculation of a parameter now known as *Allan variance*[2] in 1966 to find the optimal integration time for noisy and drifting signals. Whereas Allan used his method to characterise the quality of atomic frequency standards, Rau et al.[3] extended Allan's concept towards the analysis of microwave radiometer stability. In this paper, the latter scheme is adapted to OCT measurements.

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2. ALLAN VARIANCE AND OPTIMAL INTEGRATION TIME

The Allan variance is essentially the mean of the squared differences between two consecutive measurements of a reference target made with a given integration time. If we take the situation of an OCT device measuring the signal produced by a temporally static reference target, the measurement would theoretically result in a temporally constant signal. But in reality and with reference to the above deliberations, the measured signal is prone to noise and drifts and must be considered as a function of time, $s(t)$. If we integrate the signal over a given minimal integration time τ at time t we get a measurement sample

$$S_t(\tau) = \frac{1}{\tau}\int_t^{t+\tau} s(t')dt' \quad . \tag{1}$$

The difference between two contiguous samples is given by

$$D_t(\tau) = S_{t+\tau}(\tau) - S_t(\tau) \quad . \tag{2}$$

$D_t(\tau)$ is computed for $t = i\tau$ where $i = 0, 1, 2, \ldots, N$ and N is in the order of magnitude of 10 000. The Allan variance for the integration time τ is then calculated with

$$\sigma_A(\tau) = \frac{1}{2N}\sum_{i=0}^{N} D^2_{i\tau}(\tau) \quad . \tag{3}$$

Now, the Allan variance is subsequently computed for increasing integration times. To simulate longer integration times, averages over a given number of consecutive samples with minimal integration time τ are used. Finally, the integration time with minimal Allan variance is identified. This integration time corresponds to the optimal integration time, i.e. the signal noise is reduced without spoiling the measurement with long-term instrument drifts.

3. EXEMPLARY ANALYSIS OF AN ARTIFICIAL SIGNAL

As an illustration, an artificial signal was analysed with Allan's method. Fig. 1, left panel, shows the artificial signal being the sum of normally distributed numbers and a constant temporal drift. A single point of the signal can be considered as a sample with minimal integration time equal to 1 s as calculated with Eq. 1.

The right panel in Fig. 1 shows the Allan variance $\sigma_A(\tau)$ of the artificial signal as a funtion of integration time having used Eq. 3 for the computation. To identify the minimum Allan variance, it is convenient to plot the data with double logarithmic scale.

It can be seen that $\sigma_A(\tau)$ is high for short integration times. This is due to the noise in the signal causing large differences between two consecutive samples. $\sigma_A(\tau)$ decreases for longer integration times and reaches a minimum at approx. 150 s. Without signal drifts, $\sigma_A(\tau)$ would still decrease for even longer integration times. But the effect of the signal drift is predominant after 150 s and leads to an increase of $\sigma_A(\tau)$. It is thus useless to integrate the signal longer than 150 s.

The behaviour of the averaged signal is illustrated in Fig. 2. The three panels show averages of the signal as given in the upper left panel with three selected integration times. For the sake of clarity, only the first 2000 seconds of the artificial signal are displayed. The jumps between two consecutive measurements are larger for short (30 s) and long (500 s) integration times, and they are minimal for 150 s integration time.

4. FINDING THE OPTIMAL INTEGRATION TIME FOR AN OCT DEVICE

Fig. 3, left panel shows an example of an A-scan (depth scan) of our reference target being a microscope slide with some layers of adhesive tape sticked on it. 10'000 A-scans with an integration time of 100 μs were acquired. The refection coefficient measurements acquired at depth 280 (marked with an asterisk on the A-scan in the left panel) are distinct and therefore served as database for the Allan variance computation (middle and right panel in Fig. 3, respectively). To increase the integration time, multiple consecutive samples were averaged. It

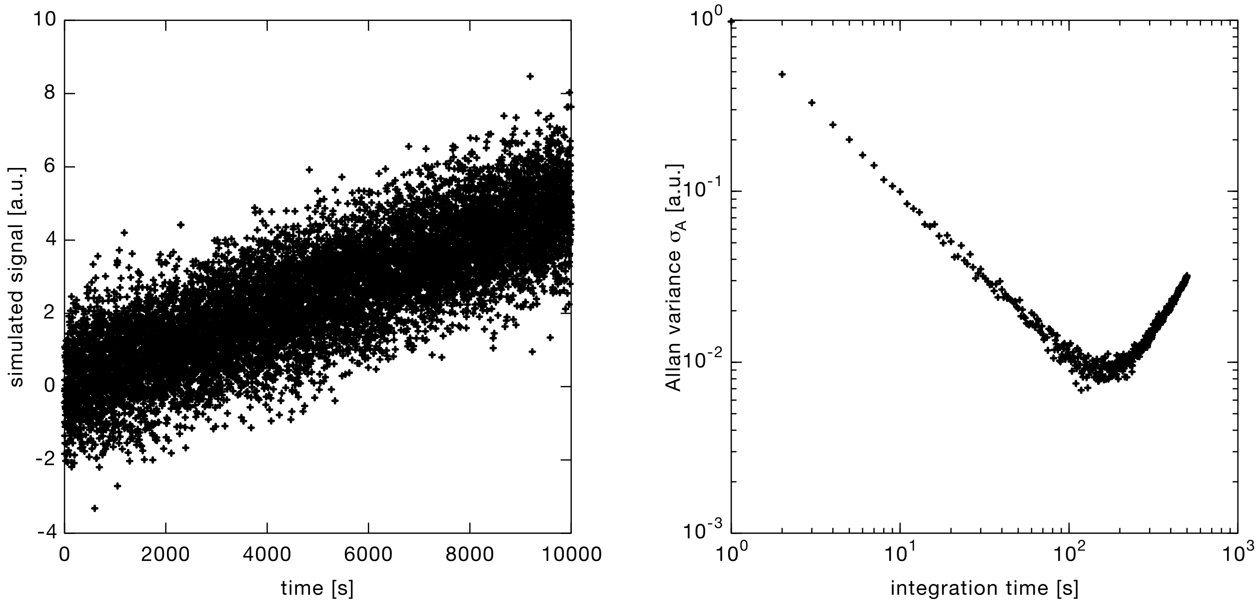

Figure 1. Left: Simulated signal with noise and drift. Right: Allan variance $\sigma_A(\tau)$ of the simulated signal as a function of integration time τ in double logarithmic representation. The optimal integration time for the simulated signal in terms of minimizing noise and drift effects is at approx. 150 s where the Allan variance is minimal.

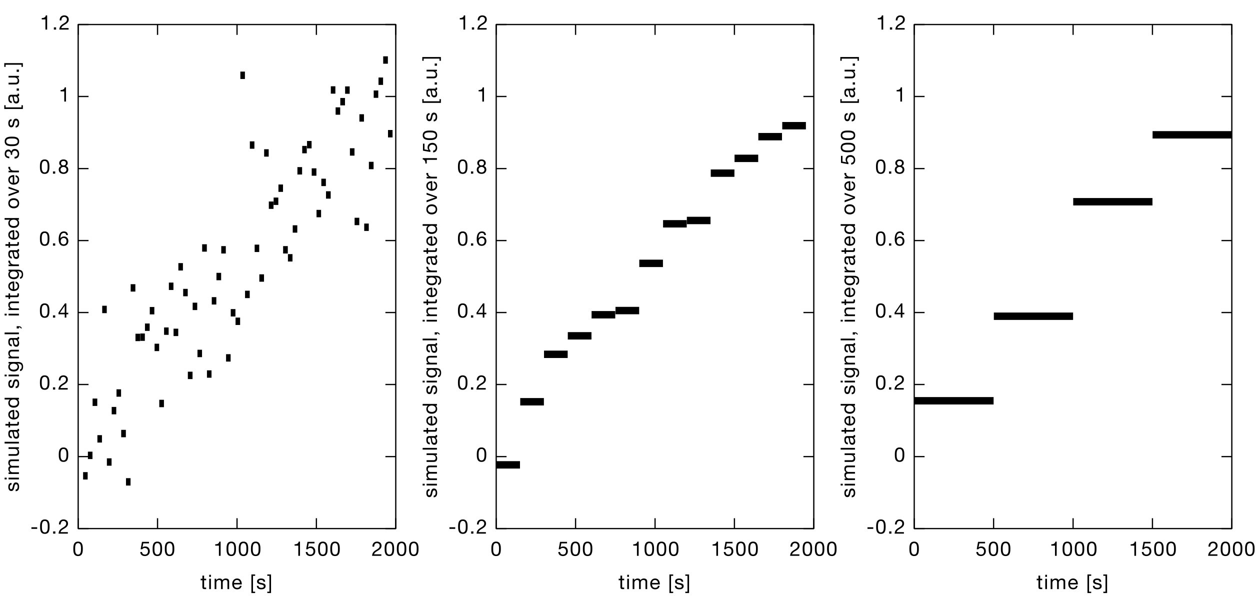

Figure 2. The simulated signal from Fig. 1 left panel averaged over contiguous intervals of 30 s (left panel), 150 s (middle panel) and 500 s (right panel). The difference between two contiguous intervals is minimal in the middle panel corresponding to the optimal integration time of 150 s.

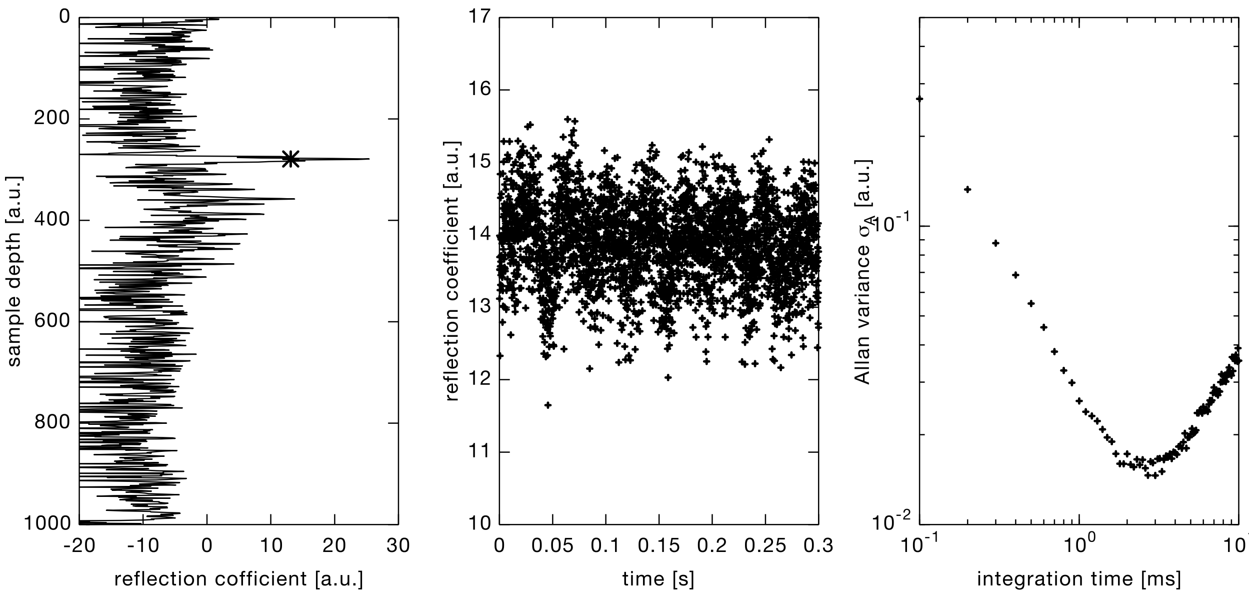

Figure 3. Left: OCT A-scan (depth scan) of a reference target (a microscope slide with some layers of adhesive tape on it) made with an integration time of 100 μs. The strong peak around depth 280 is due to the interface air—tape. The peaks between depth 280 and 500 originate from the adhesive tape layers. Being very weak, these peaks are almost hidden in the background noise. Middle: Signal at depth 280 in the A-scan (marked with an asterisk in the left panel) against time. Noise as well as a wiggle of the signal are visible. Right: Allan variance of the signal in the middle panel. The optimal integration time is achieved for minimal Allan variance at approx. 2 ms.

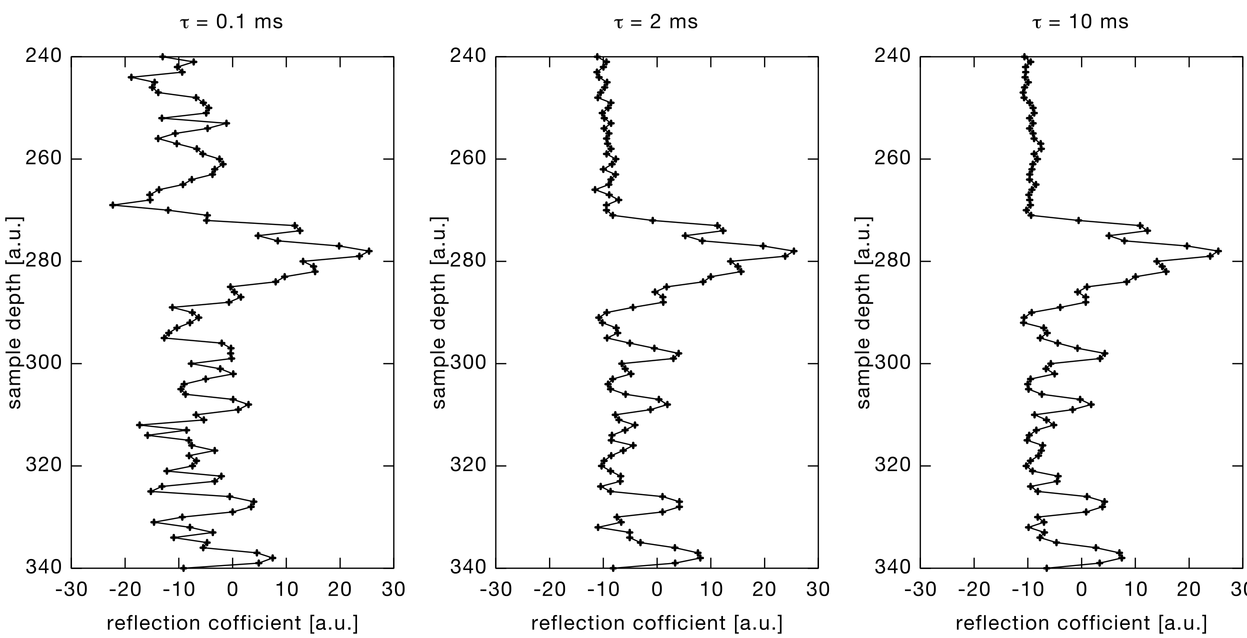

Figure 4. The three panels show A-scans of the reference target as displayed in Fig. 3 left clipped for depth 240 to 340. The A-scans are averaged over 100 μs (left panel, too short integration time), 2 ms (middle panel, optimal integration time) and 10 ms (right panel, too long integration time). The strong peak at depth 280 is well visible for all integration times. However, the area above depth 280 where no scattering objects are present is very noisy for $\tau = 100$ μs. For the optimal integration time in the middle panel, the noise is significantly reduced. If the integration time is even longer (right panel), only a small additional reduction of the noise can be achieved. The peaks below depth 280 are hardly visible for the shortest integration time. With optimal integration time they emerge from the background noise (middle panel). Again, no significant improvement can be achieved for longer than optimal integration time.

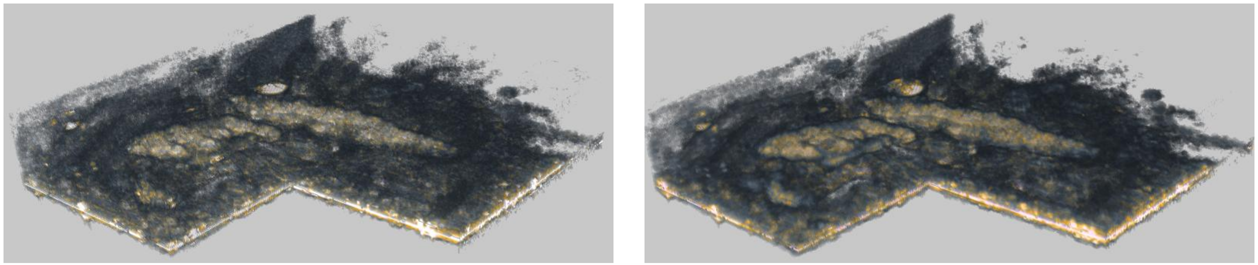

Figure 5. Pseudo-colour 3D OCT images of water inclusions in calcite. Whereas the left image was acquired with an integration time of 20 μs, it was enhanced to 200 μs in the right image resulting in reduced image noise.

is immediately visible that the Allan variance has its minimum at approx. 2 ms integration time. It is thus appropriate to integrate or average A-scans over up to 2 ms to reduce noise. For longer integration times, the wiggle as it is manifest in the signal in the middle panel of Fig. 3 deteriorates the measurement.

The three panels in Fig. 4 show A-scans of the reference target as displayed in Fig. 3 left clipped for depth 240 to 340. The A-scans are averaged over 100 μs (left panel, corresponding to the minimal integration time the OCT device permits), 2 ms (middle panel, optimal integration time according to Allan variance computations) and 10 ms (right panel, integration time longer than necessary). The strong peak at depth 280 is well visible for all integration times. However, the area above depth 280 where no scattering objects are present is very noisy for $\tau = 100$ μs. For the optimal integration time in the middle panel, the noise is significantly reduced. If the integration time is even longer (right panel), only a small additional reduction of the noise can be achieved.

Particularly remarkable are the peaks below depth 280. They are hardly visible for the shortest integration time. With optimal integration time they emerge from the background noise (middle panel). Again, no significant improvement can be achieved for longer than optimal integration time. For even longer integration times, drift effects would become visible as broadened peaks.

5. RESULTS FOR THE IMAGING OF WATER INCLUSIONS IN CALCITE

Allan's method was applied in the context of OCT imaging of water inclusions in calcite. With the optimal integration time for our OCT device found, a calcite sample with water-filled cavities was investigated, a material fully meeting the requirement of temporal stability. Pseudo-colour 3D OCT images of water inclusions in calcite are shown in Fig. 5. Bright colours represent high and dark colours low reflectivity, respectively. Weak reflections below a threshold were suppressed to reduce clutter. The left image in the figure was acquired with an integration time of 20 μs. The image noise is visible as a granulated texture on the water inclusions. In the right image, consecutive measurements were averaged over 200 μs, the surface of the water inclusion appears smoother and more easy to discriminate from the background. Due to instrumental limitations, the integration time could not be enhanced to the optimal value of 2 ms.

6. CONCLUSIONS

The Allan variance is an easy-to-use scheme to find the optimal integration time for a noisy and drifting signal: It is only necessary to acquire a measurement series of a reference target under realistic conditions, and the calculation of the Allan variance is straightforward. There is no need to know the instrumental reasons for signal fluctuations. The signal deterioration trade-off between high-frequency fluctuations and long-term changes is directly found as the integration time with minimum Allan variance. As shown in a practical example, the noise in the image is significantly reduced with an optimal integration time. This is particularly profitable for weak signals becoming better visible.

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APPENDIX A. OCTAVE CODE FOR THE COMPUTATION OF THE ALLAN VARIANCE

Copy and paste the code below into Octave[4] to produce plots similar to those in Fig. 1. Note that the naming of the variables in the code corresponds to that in the manuscript.

```
% Octave code for the calculation of the Allan variance
% Lorenz Martin, 2014

% create artificial signal (10'000 samples, noise with drift)
% supply reference measurement for s if used for real data
s = [randn(1,10000)] + [0:5/9999:5];

% define function for computation of Allan variance
function [sigma_a, tau] = allanv(s)
M = length(s); % number of measurement samples
M_max = 20; % maximum number of averaged samples
tau = 1:floor(M/(M_max)); % compute integration times considered for analysis
for itau = tau % loop for all integration times
N = floor(M/itau)-1; % calculate number of averaged samples for given tau
% calculate Allan variance:
sigma_a(itau) = sum(diff(sum(reshape(s(1:(N+1)*itau), itau, N+1),1)/itau).^2)/2/N;
end;
end;

% compute Allan variance
[sigma_a tau] = allanv(s);

% plot data (assuming minimal integration time corresponds to 1 s)
fh = figure('Units', 'centimeters', 'papersize', [12 5], 'position', [1 1 12 5]);
subplot(1,2,1)
plot(s, '.k');
xlabel('time [s]')
ylabel('simulated signal [a.u.]')

subplot(1,2,2)
loglog(tau, sigma_a, '.k');
xlabel('integration time [s]');
ylabel('Allan variance \sigma_A [a.u.]');
```